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Paper Title: CHANGING LEARNERS' UNDERSTANDINGS USING A COMPUTER-AUGMENTED CURRICULUM FOR MECHANICS

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ABSTRACT: This paper describes the development and classroom evaluation of an experimental 'curriculum' for teaching mechanics concepts to secondary school children. The curriculum integrates experiments using a series of interactive computer simulations of force and motion with real practical activities. Four scenarios were designed which underpin the sequencing of the material taught. The aim was to promote change in learners' understandings of physical phenomena, by first making them aware of the limitations of their current conceptions, and then by enabling learners to develop and use a conceptual framework which both fits with their experience and is internally consistent.

An empirical evaluation was undertaken over a 7-week period with a class of twenty-nine 12- to 13-year-olds. The intervention was found to promote conceptual change, in that the children displayed more sophisticated reasoning at immediate and delayed post-tests than their counterparts in comparison classes. Specifically, explanations asserting that motion implies a force in the same direction and those excluding friction as a force opposing motion were significantly less prevalent. An interesting phenomenon was observed in that both prior and goal (newtonian) conceptions in this domain increased.

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Changing learners' understandings using a computer-augmented curriculum for mechanics

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This paper describes the development and classroom evaluation of an experimental 'curriculum' for teaching mechanics concepts to secondary school children. The curriculum integrates experiments using a series of interactive computer simulations of force and motion with real practical activities. Four scenarios were designed which underpin the sequencing of the material taught. The aim was to promote change in learners' understandings of physical phenomena, by first making them aware of the limitations of their current conceptions, and then by enabling learners to develop and use a conceptual framework which both fits with their experience and is internally consistent.

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INTRODUCTION

Newtonian mechanics is a difficult subject to teach and to learn, and conventional instruction is notably unsuccessful in facilitating understanding of the underlying principles in students. Science educators and cognitive psychologists are now agreed that a major factor contributing to difficulties in this domain is that students hold a set of intuitive beliefs about phenomena relating to force and motion which differ from those of Newtonian mechanics. This conclusion comes from a number of research studies (Driver, 1984; Driver et al, 1985; Gunstone and Watts, 1985; McDermott, 1984). It appears that children develop underlying conceptual structures which provide

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a sensible framework for understanding and describing phenomena which fit with their experience. These conceptual structures include concepts which tend to be poorly differentiated, and the relations among them are often imprecise. These conceptions are also used in partial or situation-specific ways (Champagne, Gunstone and Klopfer, 1985). Children's conceptions are believed to derive from their motivation to make sense of the world; their beliefs are shared with other children and they accord with everyday experience (a common example is the belief that motion requires a force, consistent with much experience in a world with friction). As a result, informal conceptions - especially in areas like mechanics where pupils have access to a great deal of sensory information - are resistant to subsequent instruction. The same informal theories are present in undergraduate physicists (Viennot, 1979). Through its overemphasis on measurement and quantification, formal physics teaching can in fact hinder children in acquiring an understanding of underlying principles (cf. White and Horwitz, 1987). Consequently, while various possible outcomes for the interaction between children's science conceptions and science teaching have been outlined, in practice in the domain of mechanics the former usually remain undisturbed and scientist's science is rarely developed (although aspects of it may be learned by rote). Gilbert, Osborne and Fensham (1982) have proposed the more modest aim of developing children's awareness of the scientific viewpoint's existence and usefulness, along with teachers' awareness of children's science.

The objective of the work reported here was to facilitate change in children's conceptions about force and motion so as to enable them to reason in ways which conformed more closely to Newtonian mechanics. To this end, a computer-augmented curriculum was developed which encourages pupils to engage in meaningful learning through a process of inquiry, experimentation and reflection. It is designed for use by small groups of pupils and incorporates a series of innovative computer simulations with complementary practical activities and associated Predict-Observe-Explain worksheet tasks.

STRATEGIES FOR PROMOTING CONCEPTUAL CHANGE

Our theoretical perspective is a constructivist one; the learner is viewed as an active participant in constructing his or her own knowledge. Rather than merely being a passive process of receiving information or acquiring isolated pieces of knowledge, learning involves altering one's existing conceptual framework in the light of new experience. Conceptual change is thus considered to be a process of progressively reconstructing mental representations of events in one's environment (Carey, 1985). For this to happen, learners must make their own sense of imposed (e.g. Newtonian) ideas, extracting meaningful patterns and integrating new input with their prior beliefs and ideas about how the world works. If the new ideas are better fitted to explain phenomena, then learners may abandon their prior ideas and use another set of conceptions. This is a lengthy and difficult process.

This perspective leads to a conceptual change approach to promoting students' learning in science. This means facilitating their generation of meaning and the construction of new conceptions. Simply presenting the scientists' view or counter-examples to informal conceptions is not sufficient since learners tend to distort information to fit their prior beliefs. Moreover, the influence of strong prior conceptions may preclude children from perceiving patterns in new phenomena or from critically evaluating their interpretations of any patterns detected (Olson, 1988). Consequently dissatisfaction with existing conceptions is considered a prerequisite for change. Successful teaching must begin by promoting learners' awareness of the limitations of their current conceptions and models of the world. Since individuals may develop several conflicting models to account for different aspects of a domain or even instances of the same phenomena, revealing the inconsistencies or conflicts amongst their different models is also important in facilitating change (Anzai and Yokoyama, 1984). The aim is not for pupils to replace 'misconceptions' but to develop and evaluate meaningful understandings of multiple conceptions (cf. Bloom, 1993).

Next, learners need to be assisted in representing and refining their models. Our interventions should enable pupils to develop and use a framework which is both internally coherent and which fits with their experience. Meanings should be negotiable and new conceptions must appear plausible. Our activities are designed to provoke students to unpack, clarify, and then restructure their conceptions, making changes and extensions to their existing conceptual frameworks. New ideas and relationships are presented at specific points and students are supported in using these ideas in interpreting data. Hawkins' research indicates that a critical barrier to learning science is the failure to see natural phenomena as lawful; rather than recognising unifying principles which simplify and rationalise experience, pupils tend to treat each new phenomenon as a new instance (Hawkins et al, 1985). Our ultimate pedagogic goal is thus to assist pupils in constructing an alternative articulated set of rules for force and motion which have internal coherence. The specific focus is on fostering appreciation of qualitative reasoning in mechanics like *'as the net force acting on an object increases, acceleration of the object increases'*.

Finally, new conceptions, rules and procedures developed in one context need to be extended to a range of contexts. This again requires pupils to explore inconsistency in the use of their ideas and to assess their appropriateness in different contexts (cf. Solomon, 1983). In our case, interaction with computer simulations presenting a variety of scenarios using different representations provided this opportunity. However, to increase the number of experimental contexts, and since pupils need to be convinced that the same rules apply in the real world, physical experiments were also necessary.

In our view, the goal of practical work is integration of physical and theoretical knowledge. The rationale is to give children opportunities to experience and reason about a phenomenon; to bring their thinking into line with their experience; to observe, record and represent observations in various ways; and to make and discuss interpretations of those events. Unfortunately, practical activities rarely promote these outcomes. Pupils tend to concentrate instead on laboratory procedures for data collection and obtaining the 'right' answer, and to view school science as divorced from everyday experience. In order to minimise these tendencies, White (1979) stresses the importance of including directed hands-on experience with familiar physical objects and events. Accordingly, a sequence of practical activities have been developed which provide such experience and moreover are closely related to the computer-based ones. In both cases, it is considered essential for pupils to articulate their reasoning and their strategies. They are also asked to make comparisons between the results obtained in different contexts, with a view to confronting and resolving any differences. Elicitation of their subsequent explanations serves to create a bridge with the 'real' world. This process of comparing real and simulated motion is also known to preclude the exposure of certain errors which relate only to one context, and to help tackle the problem of pupils obtaining correct results when experimenting with a simulation, without any actual learning or development of understanding taking place (McDermott, 1991).

To conclude, our instructional approach has four components:

(1) identify and clarify prior conceptions through clinical interviews and previous protocol studies

(2) motivate pupils by presenting counter-examples which challenge those conceptions

(3) facilitate restructuring by introducing intelligible new conceptions explicitly through teaching materials

(4) provide opportunities for students to use the new ideas - and assess their appropriateness - in different contexts

Note that components (2) and (3) are not necessarily consecutive; the intention was to highlight the inadequacy of prior conceptions whilst simultaneously presenting viable alternatives.

Collaborative learning

The effectiveness of any intervention can be optimised by attending to the context in which it takes place. Typical usage of both computers and practical apparatus in schools is by small groups of pupils rather than individuals. Developmental psychology research indicates that cooperative problem-solving has advantages for learning (Trowbridge, 1987). Collaborators are likely to challenge each other with counter-examples through putting forward alternative perspectives or interpretations, thereby promoting conflict and reflection. Recent work on computer-supported collaborative learning in physics supports this, showing that tasks encouraging joint decisions promote conceptual change (Howe et al, 1991). For these reasons, subjects in all field studies worked in pairs or triads and the roles of peer interaction and teacher-led discussion were central to the curriculum design. The computer-based and practical activities are all intended to be carried out cooperatively, under the guidance of a teacher.

In conclusion, our strategies for facilitating conceptual change focussed on assisting individuals to alter their existing conceptual frameworks. Collaboration and discussion between individuals in a classroom context are believed to be an essential part of this process.

ROLE OF THE COMPUTER

Computer-based activities have an important role to play in promoting conceptual change. Interactive simulations are particularly useful because they enable users to explore and visualise the consequences of their reasoning. While computer simulations can of course never replace laboratory work, they do offer more in some ways: they take less effort to set up, are less dangerous, and they reduce demands on the student by providing automatic data logging and display facilities. They give instant feedback in the form of dynamic graphic or numerical representations of how variables are inter-related. These facilities allow students to design and carry out a series of their own experiments, requiring a more sophisticated qualitative appreciation of the problem. Simulation environments can be used to clarify the implications of Newtonian laws of motion. They also have the advantage of being devoid of the messy data of the real world, and they can be simplified or 'cleaned-up', permitting removal of particular factors affecting motion (e.g. friction) or separation of their effects (e.g. free fall can be observed with and without air resistance). Using a computer thus enables the simulation of events which cannot easily be demonstrated practically, and it turns abstract concepts and relationships into manipulable objects and phenomena. Forces can be rendered more accessible and controllable than in the real world, and physical laws can be manipulated directly.

Our previous research has involved continuous exploitation of the computer's potential through developing software tools with 'direct manipulation' interfaces. An example is *'Shopping on Mars'*, a collaborative adventure game which supports informal arithmetic calculation (Hennessy, O'Shea, Evertsz and Floyd, 1990). Its interface is based on a strong analogy to the physical world, and this literalism enhances its learnability. The notion of direct manipulation (DM) was first developed by Shneiderman (1983) and it means that a microworld's representations become so realistic and intuitive that a novice user can "Walk Up and Use" the software with minimal help or explanation. The interface becomes transparent to the user, who develops a feeling of operating directly in the simulated world. The aim here is to achieve a mapping from objects and operations in that world to the learner's existing concepts so that s/he can appropriate and internalise the concepts modelled by the system. For this to happen, simulations need to be interactive rather than passive, allowing users to conduct their own experiments.

One of the most powerful characteristics of computer simulation is that it allows us to change the rules under which objects behave, so that 'alternative realities' can be created. This allows the user to experience the consequences of breaking the physical laws, encouraging exploration and appreciation of their underlying logic. The 'alternative realities' approach provides an opportunity for comparative testing of different models (cf. O'Shea, O'Malley and Scanlon, 1990). It is of benefit especially where particular alternative models pupils already hold are of interest; alternatives can be designed to reflect commonly held prior conceptions. The rationale is that promoting conflict through awareness of a variety of possible models of a single situation, will increase motivation for change.

Experimentation with 'alternative realities' took place at an early stage in our research. A prototype simulation for investigating the effects of sliding friction on horizontal motion presented seven different worlds with the goal of identifying which one corresponded to the real world (Spensley, O'Shea, Singer, Hennessy, O'Malley and Scanlon, 1990). Promising results were obtained when 'Friction Worlds' were trialled with adult students; they promoted debate, experimentation and greater understanding of acceleration and friction.

Our work in this area has been greatly influenced by the *'Alternate Reality Kit'* or *ARK*, developed by Smith (1990). *ARK* is a graphical animated environment (implemented in SMALLTALK-80) for creating interactive simulations. All objects have a screen image, a position, a velocity and can experience forces. Everything in *ARK* can be manipulated according to the constraints on physical laws in faithful simulation of the real world. However, it has some extraordinary features too: the physical laws - such as Newton's laws of gravity - can be changed. This unique and powerful feature permits users to create their own artificial worlds and to carry out counterfactual experiments in 'alternative realities'. A series of preliminary experiments has been carried out with *ARK*, probing students' informal conceptions of the laws governing kinematics. Pairs of students using the system identified their own misconceptions and developed an improved understanding of the general idea of a conservation law (O'Shea and Smith, 1987).

Simulation tools of this kind with DM interfaces have great educational potential; they can be used to encourage children to make their implicit reasoning explicit, thus highlighting any inconsistencies or limitations in naive models. They provide motivation for change and an object for reflection and communication with others. These convictions and encouraging experiences with *ARK* led us to create our own software tools (using SMALLTALK-80 on Macintosh II computers). One is a modelling system called *VARILAB* which explicitly addresses inadequacies of primitive models; it allows children to reason by expressing their causal accounts of events as qualitative models (Hartley, Byard and Mallen, 1990). The other is a software environment for creating interactive simulations of motion under forces. *DM³ (Direct Manipulation of Mechanical Microworlds)* allows objects in motion to be observed and manipulated both informally and in a structured experimental manner. It was used to construct a series of simulations of motion in various contexts.

A SEQUENCE OF MECHANICS SIMULATIONS

From analyses of learners' conceptions and of the physics domain, a sequence of four scenarios has been developed. Each one addresses particular aspects of children's prior conceptions and supports the development of specified aspects of the Newtonian view. The four domains covered are horizontal motion (a) with friction ('Cardboard Box'), (b) with negligible friction ('Rocket Skater') and (c) with speed-dependent resistance ('Speed Boat'), followed by (d) vertical motion under gravity ('Parachutist'). Two versions of the first two [a and b] horizontal motion scenarios were developed in order to incorporate both continuous and impulsive forces. See Figures 1-4 for sample screen representations for each of these computer worlds.

The first scenario, 'Cardboard Box', draws attention to the idea that friction is a force which opposes motion. It permits comparison between motion of a box on two surfaces with different coefficients of friction. A full or half full cardboard box is either kicked or pushed continuously along a supermarket floor or a car park surface. The size of the push or the number of kicks can be controlled, and as in all of the scenarios, the subsequent motion can be observed directly and a simultaneous speed-time graph can be produced. The next scenario, 'Rocket Skater', simulates a frictionless environment in which

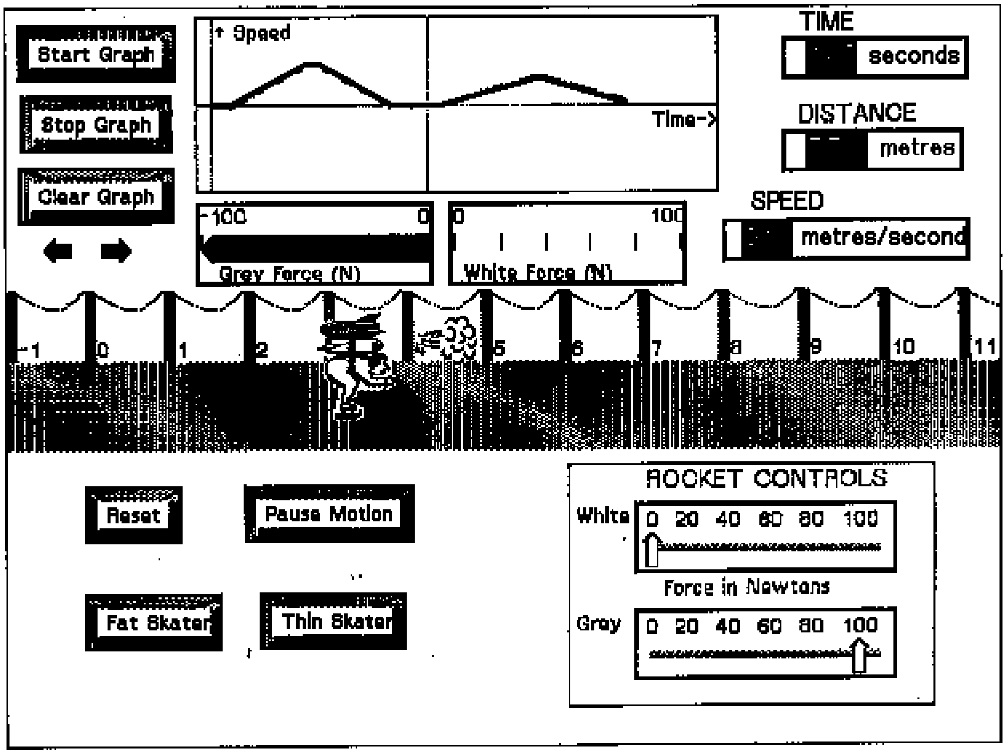


Figure 1 **<u>Rocket Skater</u> (with continuous rocket forces and mass variation)**

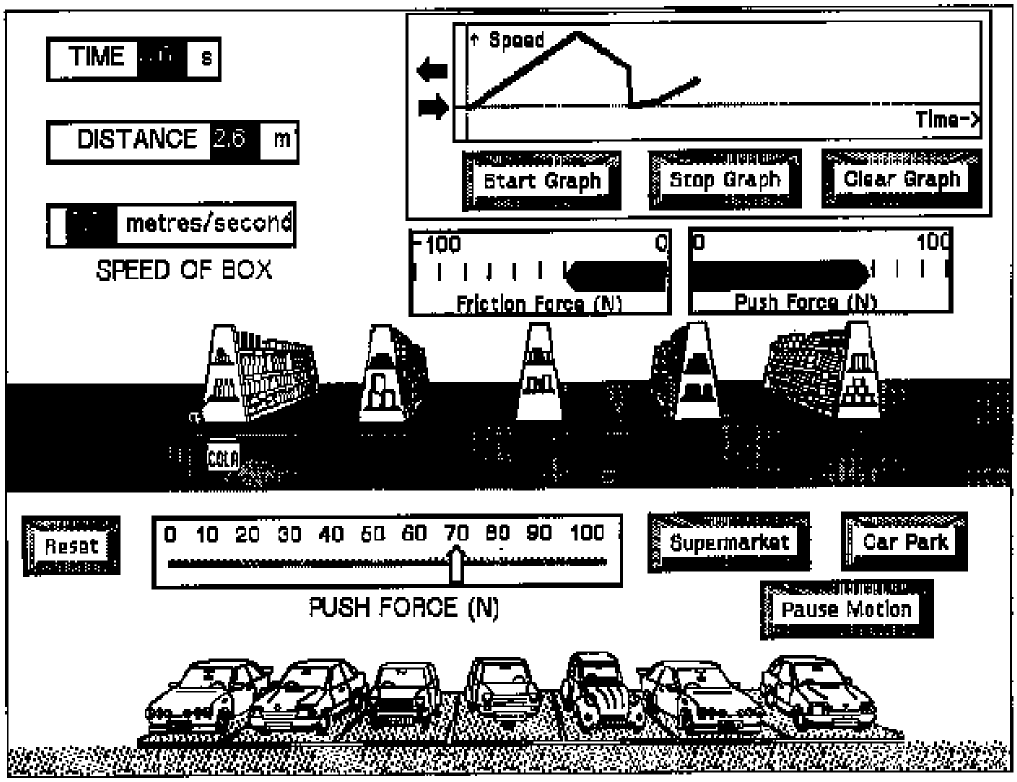


Figure 2 Cardboard Box (with continuous push force and two surfaces)

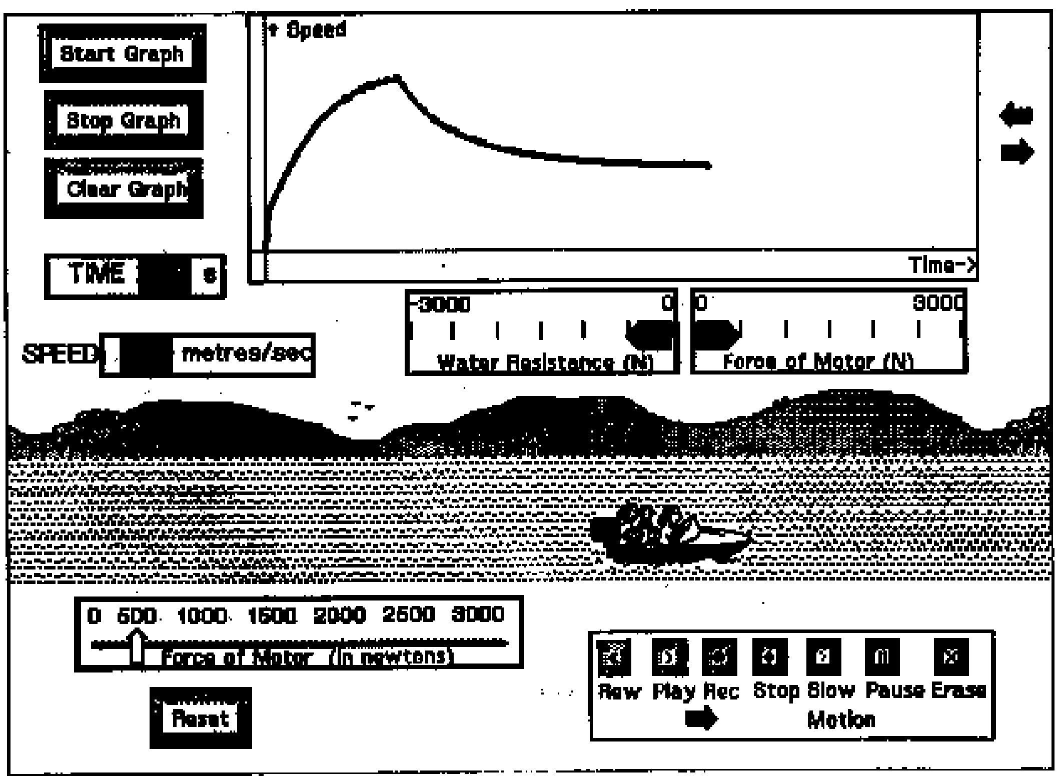


Figure 3 Speedboat (with VCR facility)

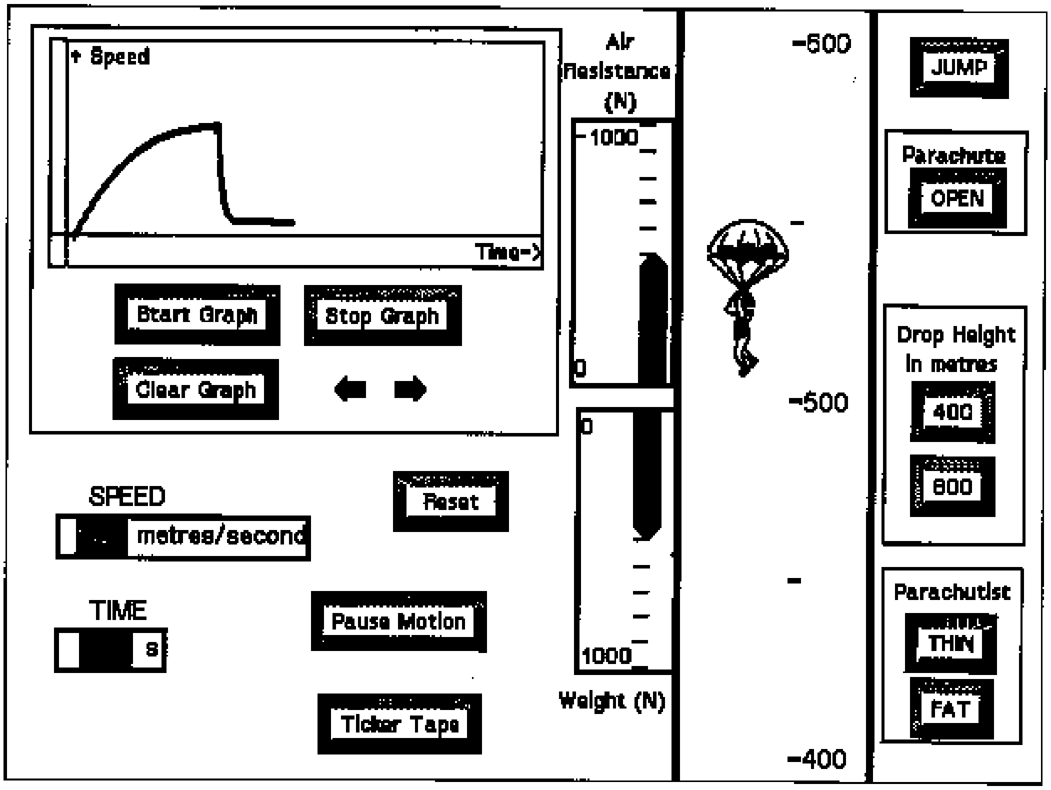


Figure 4 <u>Parachutist</u> **(with mass and height variation)**

rockets attached to a ‘skater’ figure provide either impulsive or continuous horizontal forces in a forwards or backwards direction. The mass of the skater can be varied by choosing a ‘thin’ or ‘fat’ skater figure. (The skater figure was a modified version of a cartoon figure devised by Warren, 1988.)

The ‘Speedboat’ scenario introduces the notion of a variable fluid resistive force; the throttle of the boat is under the user’s control. As the boat speeds up, fluid resistance increases and a terminal velocity is reached. The final scenario, ‘Parachutist’, involves vertical motion under gravity; the motion of a figure falling with and without a parachute can be compared and the parachute can be opened at any point in her fall. Air resistance varies accordingly. Mass and drop height can be varied.

A key advantage of DM^3 over non-computer activities is that it allows users to vary the magnitude of opposing forces with ease, visibly resulting in consistent and measurable changes in speed. The interface of the continuous force scenarios and the tasks designed to accompany them explicitly encourage students to explore the behaviour of resistive forces, the relationship between constant speed and balanced forces, and the notion of terminal velocity. To give an impression of what interaction with a DM^3 simulation involves, some of the relevant details of the interface design - followed by the kinds of tasks associated with the simulations - are briefly described below.

Interface design

Everything in each simulation environment is operated with a mouse-driven pointer which is shaped and behaves like a hand (this feature was adopted from the ARK interface, where it had proved particularly successful.) The basic features of the scenarios include a horizontal or vertical action strip with appropriate background graphics; an object(s) which can be animated; control buttons for applying uniform impulsive forces, or a ‘slider’ for applying variable continuous forces; prominent force arrows dynamically displaying the magnitude of opposing continuous forces; further control buttons for varying mass or height; digital meters for measuring time, speed of the figure or object, and distance travelled; a ‘Reset’ button; a ‘Pause Motion’ button; a graphing facility which is set up to represent speed over time. The graphing aids description of an event in relation to a user’s actions, and is linked to an on-screen video recorder. It has record, pause and slow motion replay facilities which facilitate the execution of controlled experiments. A ‘tickertape’ facility has also been developed. There is limited colour and sound feedback (control buttons can be highlighted). The user interface is fully configurable by the lesson designer; different versions of the scenarios contain subsets of the available facilities.

A planned future development is implementation of a Scenario Design Tool. This will allow non-programmers, such as classroom teachers, to create new simulations using the existing library of DM3 components, with full control over their contents and visual presentation. Editing of the scenarios will be achieved through the use of a direct manipulation interface. This development will turn DM3 into a complete toolkit for the rapid creation of tailor-made interactive simulations in this domain.

Realism

The series of scenarios makes use of both idealised and familiar, realistic situations. Some of them are 'cleaned-up' worlds, which are helpful in focusing attention on basic elements of the system or in isolating variables which are often combined in the real world. They are also useful for exploring 'alternative realities', which have been used in order to increase students' motivation for change. These permit exploration of non-Newtonian behaviour in worlds whose underlying laws of physics have been tampered with in accordance with common informal models. Some less extraordinary 'magic' worlds which allow users to manipulate forces such as friction and air resistance have also been developed. We believe that a combination of 'magic' worlds, idealised situations, simulated 'real' worlds and the real 'real' world may in fact be the best one, and our materials incorporate all of these.

THE TEACHING MATERIALS

Rationale

The simulations described above were not designed to stand alone but to constitute a key component in an integrated teaching package for mechanics. This included a sequence of linked practical activities, developed in relation to the computer-based ones, with opportunities for students to reflect on patterns they had observed. The aims were to provide (a) experiences of equivalent 'real' situations in order to help convince pupils that behaviour within DM^3 is as in the physical world, and (b) opportunities for applying explanations developed during interaction with the computer simulations. All the activities were introduced and structured through written worksheets. (Note that DM^3 on its own is a highly flexible tool with no inherent tutorial role; the teacher and the support materials provide all of the teaching input.)

The pedagogic aim was to assist students in revising their existing conceptual frameworks in line with a Newtonian perspective. This means moving from their prior conceptions towards a set of goal conceptions; we call the changes required **key reconstructions**. Note that the process of change is not likely to be a direct one; intermediate conceptions are possible and these become evident when documenting the learning trajectories of individuals. Moreover, prior conceptions are not seen as separate targetable features in children’s reasoning but as components connected within interrelated networks. There is no one-to-one mapping of prior conceptions to goal conceptions. Therefore, the change that is actually required is for learners to change their reasoning based primarily on the prior conceptions network to that of the goal conceptions network (Newtonian theory).

The identification of prior and goal conceptions

Information about the nature of the prior conceptions that students were likely to have in the domain of force and motion was obtained through a review of the literature and a further series of studies. First, an interview study was conducted with 36 pupils aged 10-15 about their predictions and explanations for horizontal and vertical motion in a variety of contexts (Twigger, Byard, Driver et al, in press). This served to identify a number of prior conceptions for us to target in the classroom study. The materials for teaching were then developed in trial form and used with two small groups of pupils over a period of several weeks. This led to further classification of the nature of the prior conceptions which were likely to be used as well as enabling modifications to be made to the teaching materials. The prior conceptions identified for the purpose of this study together with the goal conceptions are given in Table 1 and outlined in the same order in the next section. The goal conceptions are expressions of Newtonian mechanics in semi-quantitative form. This reflects our intention in the materials to encourage qualitative and semi-quantitative reasoning within a Newtonian framework.

Table 1 **Key reconstructions in mechanics learning**

PRIOR CONCEPTION	GOAL CONCEPTION
A moving object has a 'force of motion' in it The object stops when this force 'runs out'	Force opposing motion slows things down
In space an object 'drifts about'	Objects continue at a constant speed in a straight line when no force acts on them
Friction is not identified as a force	Friction is a force which acts in a direction opposing motion
Driving force must be greater than resistance for object to move at a constant speed	Driving force equals resistive force when object moves at constant speed
An object moves in the direction of the applied force	An object accelerates in the direction of the net force. If this opposes motion then the effect of this is for the object to keep travelling in the opposite direction to the force, but slowing down
Heavier things are harder to get going, harder to keep going, and stop more quickly	More massive things are harder to get going and to stop going. Where gravity and friction act, the increased mass gives increased weight and increased friction, which combines with the increased mass effect to make acceleration harder, but on deceleration, the increased mass counterbalances the effect of the increased frictional force.
Heavier objects fall faster than lighter objects	Objects of different weights fall with the same acceleration (ignoring air resistance).

Key reconstructions

The key reconstructions which, from our analysis, are required of learners, are as follows. Firstly, pupils believe that moving objects stop eventually, and that a moving object has 'force' or 'energy' in it which acts in the direction of motion and keeps it going. The object is thought to stop moving when this 'force' gets used up. (Thus a constant applied force is needed to maintain motion, as elaborated below.) In the context of space, objects are thought to just wander around. From a Newtonian perspective, a moving object keeps going in a straight line at a steady speed unless a force changes the speed or direction of its motion. Pupils tend to focus on obvious applied forces only, being less aware of other relevant forces such as friction and air resistance and hence of (a) their causation of slowing and stopping and (b) their combined effect with applied force to give 'net' force. Secondly, pupils' view of friction may be limited to rubbing between surfaces (often pictured at right angles to a surface). Their general tendency to look for a single salient causal factor in any physical situation (Driver, Guesne and Tiberghien, 1985) means that either gravity/weight or friction may be seen as critical. Alternatively pupils may conflate the effects of these separate factors. From the Newtonian perspective, on the other hand, friction is a force - with associated magnitude and direction - which acts in a direction opposing motion.

A third set of prior conceptions holds that a constant applied force produces constant motion, a larger force produces a greater constant speed, and acceleration is produced by increasing the force. This description is suspected to be due partly to pupils' undifferentiated representations for motion. They do not clearly differentiate acceleration from high constant speed. In the Newtonian formulation, a constant (net) applied force results in a constant acceleration and a larger (net) force results in larger acceleration. The absence of a notion of balanced forces and pupils' tendency to seek a sole causal factor leads them to argue that driving force must be greater than - instead of equal to - resistive force (F>R) for constant speed. They may believe that some excess force in the direction of motion is necessary, or they may be failing to distinguish between the 'getting going' and 'keeping going' phases of motion. Since many students hold a limited view of motion which focuses on speed rather than acceleration, it is even more important that they come to recognise the distinctions and relationships between the different phases involved when an object moves (rest, acceleration, constant speed, deceleration). Each of these requires a different force explanation; for instance, getting an object going demands that F>R whereas keeping it going needs F=R.

Pupils tend to have prior conceptions which involve an undifferentiated notion of 'heaviness' as a causal factor in horizontal motion, used as an intervening variable in explaining how objects will move. Thus heavier objects will be expected to be 'harder' to get going, 'harder' to keep going, and to slow down more rapidly. Essentially this use of 'heaviness' is a conflation of mass, weight and friction. For some pupils, the notion may be unpacked to include reasoning of the effect of weight on friction, which acknowledges that increased weight causes increased friction, but there may then be confusion as to whether or not weight should also be included as a resistance force in its own right, in addition to its effect on friction. There is usually no sense of the effect of inertial mass as opposed to weight. Thus, where there is no weight, as in outer space, objects of different mass may be expected to behave similarly. Pupils must recognise the separate inertial effect of mass, that a bigger mass consistently requires a larger force to give it the same rate of change of motion as a smaller mass, and must also see how it combines with the weight/friction effect. In the case of vertical motion, pupils will usually predict that heavier objects fall faster, rather than at the same rate of acceleration (if air resistance is ignored).

Strategies

The teaching materials were designed to facilitate the key reconstructions outlined above through various means. Both the practical and computer-based activities focussed on the recognition that there are distinct phases of motion, usually emphasising this further by incorporating a graph generation or interpretation task (see sample worksheet tasks in Figures 5a and 5b). The activities also highlighted the factors of influence during each phase, for instance by requiring pupils to manipulate variables such as mass and height, observing consequent variations in speed. Ticker tape facilities - usually physical ones but sometimes on-screen - were heavily drawn upon as indicators of speed, the tape chart patterns produced being compared with the shapes of speed-time graphs on the screen. (Note that in order to help develop a basis of understanding, and since the work concentrated on developing materials for young pupils, i.e. 12- to 13-year-olds, no numerical calculations were demanded.) The object of these activities was for pupils to derive qualitative relationships between the relevant variables and to relate these relationships to underlying principles. Encouraging this kind of exploration of the behaviour and effects of forces was intended to help build the notion of **net** force and to link it to **changes** in motion.

The computer-based activities moved towards this goal by asking children to collect empirical data about prototypical motions and to identify simple relationships between variables in the computer world. The idea was to highlight similarities between the scenarios once their differences had been perceived. DM^3 deliberately presents an opportunity for pupils to construct a Newtonian set of rules relating notions of force and motion on the screen. The software is designed to make the rules as apparent as possible through devices such as real time graphing and force arrows on the screen representing the magnitude of the forces acting on an object at a particular time. Relationships between features such as the size of the force arrows and the slope of the speed-time graph can be observed directly. Newly developed rules can be used to predict and produce particular motions within the scenarios, and consequently to describe and explain ‘real world’ behaviour.

Since the aims of the activities included getting pupils to construct progressively more elaborate rules, to generalise their new conceptions across a range of contexts, and to extend them to increasingly complex situations, the order in which the activities were presented was clearly of importance. Our view of a successful instructional sequence is one which revisits particular cases in increasing detail: idealised ones which simplify the underlying physics (e.g. frictionless worlds), and those which pupils have experienced themselves (e.g. the behaviour of everyday objects under friction).

Table 2. **<u>Sequence of actitivites: goals and contexts</u>**

TARGET CONCEPT	ACTIVITY CONTEXT
description and explanation of distinct phases of motion: speeding up, constant speed, slowing down.	introductory task: 'moving a pram' card sort activity 'Cardboard Box' Alternative Realities
a threshold force must be applied to get an object moving; the motion produced is acceleration	pushing a box physical world experience 'Cardboard Box' scenario
as net force increases, acceleration increases; force arrow representation	trolley practicals 'Cardboard Box' scenario
frictionless motion; net force gives acceleration; as mass increases, acceleration decreases	linear air track demonstration; trolley practical; 'Rocket Skater' scenario
net force under balanced and unbalanced forces and effect on motion	'Rocket Skater' scenario
varying mass has an effect on changes in motion; frictionless motion - no mass effect at constant speed	thought experiments, 'Rocket Skater' optional experimentation, 'Cardboard Box'
varying surface has an effect on motion	sledges practical; 'magic' version of 'Cardboard Box' scenario with control over friction coefficient
phases of motion produced by an impulse force	hitting a box practical impulse version of 'Cardboard Box'
balanced forces; deceleration results from a net force opposing motion	discussion/ written review exercise

vertical motion through fluid; decreasing acceleration, terminal velocity; speed-dependent resistance	dropping ball bearings practical; 'Speedboat scenario'
free fall; type of motion, terminal velocity; effect of mass change; removal of air resistance	dropping plasticene balls; 'guinea & feather' demonstration; 'Parachutist' scenario
connections between factors affecting motion	concept mapping

This led to creation of a sequence of interrelated computer worlds and practical situations increasing in complexity, by gradually introducing more variables and more complex inter-relationships. In the computer worlds, this included more extensive functionality, allowing greater pupil participation. This progression is illustrated in Table 2, which contains a list of the target relationships and ideas underlying our curricular sequence of computer, practical and reflective activities (including the contexts in which they were set).

The computer activities were presented in the order in which the scenarios were introduced above (in ‘A sequence of mechanics simulations’), with the ‘Cardboard Box’ scenario additionally being revisited later. The first lesson exposed pupils to four ‘alternative reality’ versions of ‘Cardboard Box’ (whose interfaces contained a minimum number of DM^3 features), in order to elicit prior beliefs about what happens when a box is pushed and then released. The task was to detect the simulated ‘real world’ by comparing prior expectations with behaviour observed in each alternative world and in a real situation. Two subsequent ‘Box’ scenarios then introduced the graphing facility, force arrows and the second surface. ‘Rocket Skater’ with first single mass and then dual mass followed. Two further ‘Box’ scenarios introduced the tickertape facility with dual mass, and then a ‘magic friction’ slider, allowing pupils to explore differences arising - mainly in initial threshold forces - with five surfaces. Next came two impulse versions of ‘Cardboard Box’ (single mass and dual mass) and then ‘Speedboat’ with an on-screen VCR; this scenario introduced the notion of a variable resistive force, which was further developed in the final scenario: ‘Freefall’. The first version of the latter had two drop heights plus vertical tickertape, and the second had dual mass and height plus a VCR.

Worksheets

Iterative field testing of the simulations was carried out using "Predict - Observe - Explain" tasks and this culminated in development of a set of worksheets for guiding pupils through the computer-based and associated practical activities. The worksheets required written responses from pupils (see Figures 5a and 5b for sample worksheet tasks).

The strategy employed was first to obtain descriptions of motion and the relevant forces believed to be in operation, and predictions about outcomes. Pupils were then asked to carry out experiments - either within a simulation or with real equipment - with the aim of testing and refining those predictions. Hence they observed events which may have contradicted their prior conceptions, experiences and models. The pupils were required to formulate causal accounts of their observations, and where appropriate, to explain different results arising from the practical and computer activities. The focus of the later lessons in particular was pupils' transfer of newly developed rules to new situations, so those lessons made more use of investigation and application.

Each worksheet contained a set of activities related to one of the computer scenarios or practical/other contexts. In keeping with our previous research indicating that multiple representations of a problem can impede novice physics students (Scanlon and O'Shea, 1988), the number of different types of task was kept to a minimum and similar tasks were presented in the same format each time.

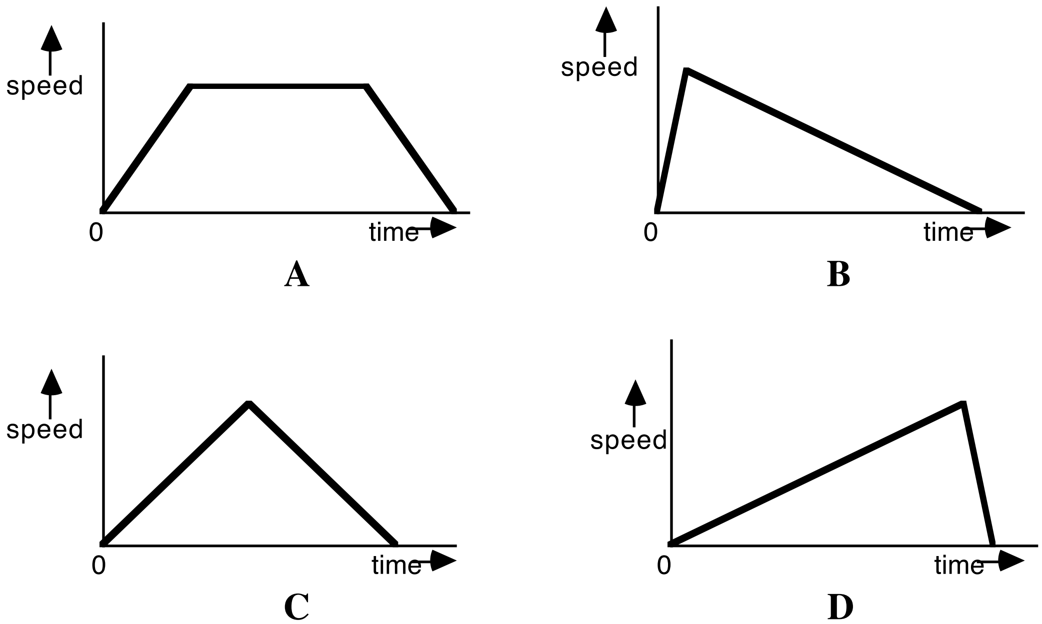
Some activities were directed, some more open-ended and thought-provoking, and others involved very specific tasks such as achieving constant speed. Consistent use was made of 'rule sort' tasks at the end of an activity - whereby pupils determined whether rules of the form "*In order for the boat to go faster and faster, the force pushing it must get bigger and bigger*" or "*When the push is bigger than friction, the stationary box will speed up*" were true or false. These tasks served both to direct pupils' thoughts and to assess their progress.

Figure 5a
<u>Sample worksheet tasks from a computer-based activity:</u>
<u>Cardboard Box with impulsive forces</u>

You have spent quite a lot of time learning about **pushing** the box. But what will happen if you **kick** it instead? One way to think about it is to imagine a kick as a **large force** applied for a **short time**.

YOUR TASKS

1 Before you use the computer, **predict** which of these shapes of graph you expect to get when the person kicks the box in the supermarket. **Explain** your choice.[2]



2 Try it out **in the supermarket** and see if you were right. Did you predict correctly?

3 Think carefully about the graph, and answer these questions.

a Which is steeper, the acceleration or the deceleration? Why is this?

b Why is there **no constant speed** section in the middle of the graph?

4 Now think a little more and again **predict** before you use the computer.

Draw in your answers in the spaces below.

a What would the graph look like if there were **two** kicks - the second kick **after** the box had stopped moving from the first kick? *(axes provided)*

b Try it out and see if you were right. Did you predict correctly? If not, draw in the correct shapes on the graphs above and label them 'correct'.

5 What difference does it make if the box is kicked in the **car park,** instead of inside the supermarket? **Describe** and **explain** what happens.

6 What would happen if there was **no friction**? **Explain** your answer.

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[2] An icon showing a hand writing on a sheet of paper (plus several lines of blank space) appeared after each task requiring a written response.

Figure 5b **<u>Sample worksheet tasks from practical activity 'Hitting the Box'</u>**

Earlier you found out what happens if you **push** the box. But what if you **hit** it?

YOUR TASK

Find out what happens if we hit a box with books in. Take care that the box does not fall onto the floor.

1 Have a few practice attempts at hitting the box so that it moves about 1 metre across the table.

2 Attach some ticker tape to the back of the box. Switch on the ticker tape apparatus. Hit the box across the table.

3 Look carefully at the pattern of dots on the tape. Describe clearly the spacing of the dots and the motion which is shown.

4 Now make the tape into a tape chart, using pieces which are **five** dots long rather than ten. Stick the tape chart into the space below.

5 Describe carefully the motion shown by the chart.

6 Draw a speed/time graph which shows the motion you have described. *(axes provided)*

7 Why does the box slow down and stop?

8 Predict what would happen if the box was on a frictionless surface. Explain your answer.

EMPIRICAL EVALUATION

The materials developed - the interactive simulations and all associated activities - have been extensively piloted and field tested with 375 secondary school students between the ages of 12 and 15 (plus 60 adults). The methodology underlying their development and trialling is outlined in an overview of the ‘Conceptual Change in Science’ project (Twigger et al, 1991). The work culminated in a large-scale classroom intervention with twenty-nine 12- to 13-year-olds. This experiment was carried out in order to examine both the processes of conceptual change and the effectiveness of our computer-augmented curriculum in promoting learning. It assessed the impact of our sequence of scenarios, when supported by practical work and guided discussion. Some methodological issues underlying the design of the study are discussed before its results are reported. These issues were elaborated further by Draper et al (1991).

Measuring conceptual change

In order to measure the success of the curriculum in promoting learning, the first decision made was to run a large classroom trial using pre-, post- and delayed post-tests. The investigators wanted to aim for more than the minimum of demonstrating a simple effect in terms of the intervention being better than nothing. The next criterion was to show that the intervention could improve children's understanding in well-documented areas of difficulty which arise at many ages. Diagnostic tests were thus designed to assess change in terms of the specific key reconstructions identified earlier; they incorporated both multiple choice questions and prompts for explanations of children's reasoning. Two issues then arose: firstly, the difficulty of teasing out which components of the curriculum, if any, were critical in promoting change - the worksheets, computers, or working in groups, for example. The sheer novelty of using computers intensively or working under the scrutiny of researchers with a video-camera may even have been contributory factors. Secondly, written tests could demonstrate a net effect only. It was clear that the process of change needed to be examined and the cause of any effect identified in order to begin to address these issues. An intensive case study of one small 'target' group of three pupils within the class was therefore undertaken and audio-tape and extensive written data were collected on a further two groups. Detailed interviews using techniques developed during the pilot testing were also carried out before and after to investigate changes in sophistication of the reasoning and vocabulary used by these nine pupils. The small group data proved very rich and provides at least a starting-point for investigating which parts of the intervention were apparently effective in changing the learners' conceptions. Its analysis constitutes a study of its own within the larger study (a report is currently being prepared for publication by Driver and Twigger).

Ecological validity

It was felt that even though an innovative and sophisticated curriculum has significant value if it is shown to promote conceptual change in individuals or small groups alone, its value is nevertheless limited if that change takes place outside the context of a normal teaching environment. Studies of this kind usually involve an unrealistic commitment of time from a teacher or researcher. A far more challenging task was therefore undertaken: evaluating the usability and effectiveness of our materials within the constraints of an ordinary classroom setting. Since powerful microcomputers are expensive and still scarce in schools, and in any case, computers are rarely found in science laboratories, it was necessary to look to the future in creating a suitable environment for presenting our materials. This meant setting up a situation where several sophisticated but user-friendly computers were brought in for the purpose. The computers were used by pupils interchangeably with a range of practical activities involving the typical apparatus of secondary school science, within their normal timetable, under the supervision of their usual teacher, and within the confines of a smaller than average laboratory.

Aims

The main aims of the classroom intervention were as follows:

1. Measurement of conceptual change over time, in comparison with groups having conventional teaching about force and motion but no exposure to DM^3.

2. Detailed qualitative analysis of learning in action, focusing on individual change within small groups of pupils.

3. Evaluation of the usability of our materials within the constraints of an ordinary classroom setting.

The hypothesis tested was that engaging small groups of novice science students in activities which clarify the consequences of using a force model would produce qualitative change in their perceptions and understandings of phenomena in this domain. While a full set of Newtonian conceptions cannot be expected to appear, it was hoped to provoke students to reassess, revise and restructure their existing conceptions to some extent, resulting in more sophisticated ideas, more precise and meaningful explanations of motion, more differentiated concepts and greater understanding of their appropriateness in different contexts.

METHOD

The experiment took place during the Science lessons normally allotted to the class under investigation for the topic of 'Force and Pressure'. The instructional period occupied 7 weeks with 3 sessions per week, two of 50 minutes and one of 1 hour and 20 minutes duration. The final session was devoted to a written post-test. The total instructional time (including 2 hours of unrelated administration) was approximately 20 hours over 20 sessions.

The experimental period was preceded by 2 weeks (6 sessions) of pre-trialling, during which time all the practical arrangements were finalised and pupils were introduced to their new situation. A written pre-test was also administered and pre-test interviews were carried out. (The software used during this time was a painting package and bore no resemblance to the experimental software.)

Subjects and teacher

The instructional group comprised a mixed ability class of 29 children aged 12 - 13 (13 boys and 16 girls) from a secondary school in Bletchley, Buckinghamshire. Lord Grey School is a comprehensive with about 1000 pupils aged 12 - 18. There is considerable variation in both its pupils' socioeconomic background and their ability range. Computer provision is substantial and Information Technology courses are offered at several levels. Our sample of pupils all had prior experience of microcomputers and could operate a mouse. They had studied an Integrated Science foundation course for only one term previously and had no prior experience of formal instruction in mechanics or physics in general at secondary school level.

The teacher of our sample class was female and aged 50. She had an Open University degree in Science and Education, focussing on Chemistry, and 10 years experience of Science teaching at secondary level.

Groupings

The class was divided into 10 small groups (9 triads and 1 pair). Groupings were decided by the teacher, in consultation with the researchers. The rationale consisted of choosing collaborators who would be willing to work together over an extended period of time, using friendship groups where possible, whilst avoiding the combination of certain troublesome boys within a group. (The children normally worked in similarly-formed groups of three - with a few pairs - for practical work in this teacher's lessons.) Success of the groupings was assessed during the pre-trialling period, after which the combinations were finalised. Only one mixed-sex group appeared to be cohesive enough to remain fixed after this trial. On the basis of observation during pretrialling, three groups were designated the target group (all female) and the reserve target groups (one female group and one male group). The criteria for selection in each case was a mixed ability group who were articulate and appeared to work cooperatively.

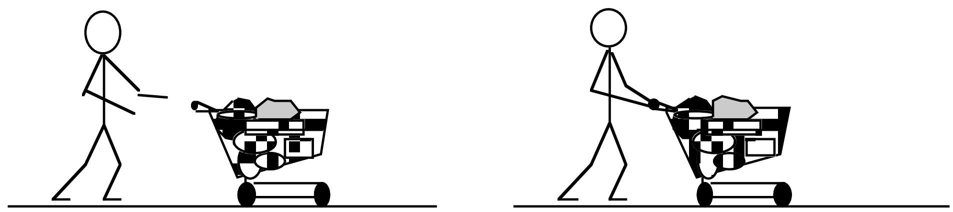
Diagnostic testing

Information about the pupils' conceptions before and after the teaching was obtained from a diagnostic written test (described below). In addition, the 9 pupils in the target groups were the subject of pre- and post-test interviews. This series of clinical interviews provided the most in-depth means of measuring learning gains as a consequence of our interventions. There were three independent interviewers, all of whom were female and had a background in science education. Each questioned the members of one of the target triads on two occasions, once the week before the intervention began, and again within two days after it had ended.

The procedure involved tape-recorded dyadic discussion in private, using a series of pictures of situations involving objects in motion. This technique was used to prompt students' understanding of the physics underlying the motion depicted. The interviewer began by presenting directed questions and then followed these up with a series of more general open-ended questions and thought experiments, concerning three contexts: 'kicking a pebble', 'throwing a ball up', 'riding a bike'. The contexts were selected to probe pupils' reasoning in each of the areas in which key reconstructions were identified. Each situation was related to several items on the written diagnostic tests. The basic ideas covered were the 'force in object' notion and comparison of the effects of two forces: driving and resistive forces. The interviewers elicited explanations concerning each instance, attempting to give non-evaluative responses and pursuing until they had gained an appreciation of the pupil's ideas. They referred explicitly to the interviewee's pre- or post-test responses as appropriate, requesting clarification and additional explanation. Full transcripts were made.

The interview results were corroborated using written tests. A set of 15 diagnostic tasks, each illustrated with a diagram, was developed for presentation to the whole class as pre-, post- and delayed post-tests. (See example of test item in Figure 6). 12 contexts concerning horizontal motion with and without friction (space) and vertical motion through air were covered. Some of these were identical or similar situations to those presented by our computer simulations (pushing a box, flying saucer with two rockets, pulling a boat, parachuting). The test was designed to elicit reasoning relating to each of the key reconstructions identified including force and motion, balanced forces, friction as a force, resistive forces in general, speed-dependent resistance, the effect of mass on change in motion, and the various different phases of motion. The diagnostic test results for all subjects, together with the interview outcomes for the three target groups, could thus be related to the reconstructions we had identified as significant goals of our instructional intervention.

Figure 6 **<u>Sample Diagnostic Test Item</u>**



When you go up to a heavy shopping trolley and push it to get it moving, do you push:

tick one box

- [ ] A harder than
- [ ] B softer than
- [ ] C the same as

0 1 2 3

how sure are you?

when you are walking along keeping it going at a steady speed?

Explain why you chose this answer.

Two speed-time graph interpretation tasks were included in order to assess development of children's skill in this area, as a consequence of engaging in activities drawing on the *DM*^{3} graphing facility. The tasks had all been pilot tested extensively beforehand, beginning with the interview study conducted by Twigger et al (in press). The items were refined during subsequent trials with children in a variety of secondary schools, as reported in Twigger et al (1991).

The test had a multiple choice format, with most of the 26 questions presenting a choice of three responses (a few had four or five and some permitted multiple selections). For example, one item asked; "*Suppose that you drop two identical balls from different heights. Both balls are dropped at exactly the same time. Which ball is going faster when it hits the ground (lower ball / higher ball / both at same speed)?*" Although pupils often do not explain their reasoning clearly, explanations were requested in order to help identify the reasons for their choices, and to provide richer information about their thinking. This was particularly helpful since as with most instruments of this kind, each of the choices could have been selected for a variety of possible - sometimes even conflicting - reasons. One disadvantage is that pupils may have felt a need to write something simply in order to fill the space. To give them the chance to show when they were guessing and to avoid inferring too much from those responses, a 0-3 confidence scale was attached to all questions and prompts for explanations. Clear statements accompanied by a confidence rating of 3 were deemed to be the most representative of a child's reasoning.

The order of item presentation is known to constitute a common source of bias upon test responses. Since some of the tasks were related in content, their order was randomised. Each subject received a personalised test, three identical forms of which were presented (a) 1 week before the first instructional session, (b) during the final session of the experimental period and (c) after a further 5 weeks. No instruction in this domain took place between the post- and delayed-post tests. Tests were conducted under examination conditions and as much time as necessary was allowed; typical completion time was 30-40 minutes.

Following the same procedure, the test items were presented to 3 additional mixed ability classes (with approximately equal numbers of girls and boys) before and after they underwent their usual initial teaching on the topic of Forces. One class (N = 26) called ‘Class 2’ was in the same year group at Lord Grey School and they were also given a delayed post-test; their 6-week course (17 hours) covered general aspects of horizontal and vertical motion under forces. The other comparison groups were two classes of 13- to 14-year-olds in comprehensive schools situated in Leeds and Kirklees. (Initial exposure to the topic in these schools customarily took place a year later than at Lord Grey.) ‘Class 3’ (N = 22) spent 7 lessons (9 hours) studying the Salters science module "Safe Journey" while ‘Class 4’ (N = 20) studied a 6-week course (8 hours) which appeared to be most similar to our own curriculum.

Since these classes were all taught by different teachers (owing to a last-minute timetable change at Lord Grey in the case of Class 2) and the teaching they received varied in length and content, they were not intended to be ‘controls’ in any strict sense for our sample class. The purpose of this exercise was to assess the representativeness of the pre-test data from the sample class and to assess what learning in terms of the set of goal conceptions takes place during the conventional teaching process.

Materials

5 Macintosh II microcomputers (with 8Mb of memory) were used to run DM^3, providing sufficient machines for half the class to use at any one time. Equipment for the practical work was all supplied by the school and included: tickertape machines, force meters, weights, rules and stop clocks, linear air track, trolleys, sledges, large cylinders, evacuated cylinders, marbles and ball bearings, plasticene, and various liquid media.

Worksheets were used to guide pupils through the computer-based and associated practical activities, individuals being required to record their written responses at each stage. (Illustrations of worksheet tasks were given in our previous paper: Hennessy et al, 1993.) Homework sheets were also provided; these largely contained practice exercises based on the activities carried out in class. In keeping with the usual procedure in this class, homework was given out once a week and marked by the teacher.

Teacher briefing

The teacher had limited opportunity to try out the materials with children beforehand, but she was given access to all of the software and materials in advance, as well as videotapes of field trials of some activities. The pedagogic aims were made clear verbally and stressed through extensive written teacher notes provided for each lesson. The notes also gave advice on organisational matters and suggestions for class or group discussion, based on our prior experiences of trialling the activities. Any issues arising were discussed with the research team before and continuously throughout the experimental period.

Lesson organisation

The class was divided into two sets of 5 small groups so that half of the class could use the computer simulations whilst the other half were doing related practical or written work. (There was no significant difference between the pre-test results from the two large Groups I and II.) The three target groups belonged to the same Group (I). Half of the time available over the 7-week period was spent at the computers.

The machines and software were set up and dismantled by the researchers so that no technical input from the teacher or pupils was required. The five computers were placed on adjoining tables down one side of the room. The other side of the room was given over to the practical and written work, normally carried out at three large tables. (Layout was constrained by the peripheral positioning of power points.) The target group was situated in the same location each time for computer work and (alone) at the same nearby table for practical work. The video camera thus had an unobtrusive set position which was convenient for filming the two kinds of activities. The reserve groups also sat at the same computer locations each time, next to a tape recorder.

The research team provided all the written materials necessary to guide the pupils through the tasks, and the teacher notes occasionally made suggestions for class discussion topics, but the lessons were basically structured by the teacher. The general pattern was as follows. A session typically started with a brief introduction from the teacher; she frequently encouraged children to work cooperatively and discuss their ideas. Occasionally she gave minimal feedback about homework or discussed a particular concept; the introduction then took up to 15 minutes. Class discussions were more common in later weeks and usually involved the teacher explaining a principle using diagrams drawn on the board whilst holding a question-and-answer session with the class. Following her introduction, the computer groups were asked to begin their tasks, whilst the practical groups usually gathered around one table for an introduction to the experiment. This was usually repeated on the second occasion the practical was carried out, and depending on its complexity, took between 5 and 10 minutes.

Once both halves of the class were working, the teacher circulated amongst the practical groups, checking on their progress and answering any questions. She was open to dealing with any problems encountered by the computer groups but these rarely arose in the form of a direct approach to her. Most of her time was devoted to management and briefing, particularly of those groups doing practical work. Little time remained for checking whether the children were understanding the lesson rationale points.

A changeover of activities occurred at the mid-point of the longest session each week. Group work subsequently continued as before; pupils who finished early were given additional tasks by the teacher or a homework sheet to commence. The practical groups were asked to clear up about 5 minutes before the end of the lesson. The teacher then drew the lesson to a close.

Within the novel framework of organising two separate large groups and a significantly reduced proportion of practical work, the lesson plans we provided did not require the teacher to alter markedly her usual teaching style. One difference was a much greater emphasis on written instructions - which reduced the need for repetition - and written responses. From the pupils' point of view, there was greater demand upon them to make predictions, to reflect upon what they had observed and learned, and to express this in writing or occasionally during class discussion.

Observation

The three target groups were monitored more closely than the other seven groups, the reserve groups being audio-recorded and the target group being video-recorded throughout (using a remote microphone). The camera was actively focussed by a full-time operator, mostly on the screen during computer work, and on the whole group otherwise, but close-ups of individuals were filmed during significant events or interactions. The target group and the reserve group of boys were each continually observed by a researcher who sat near them, taking detailed notes against a time line and intervening only for clarification. Written records included the activity being undertaken, how the group was tackling it and their individual interpretations, their roles within the group, and their interactions with others.

Another researcher monitored the whole class with the aim of describing an overall picture of the classroom culture as the pupils and their teacher engaged with the activities. This monitoring involved taking notes with a focus on three areas: (1) communications between pupils, including the extent to which knowledge was shared between pupils in different triads; (2) general observations about how the class was progressing, especially in terms of the success of the groupings; (3) any wide-scale problems encountered by the pupils, as evidenced by repeated requests for help with particular tasks or software features. (The same researcher was also responsible for providing technical support where necessary.)

This monitoring process was backed up by a series of tape-recorded structured interviews with the small groups and the teacher. During the final 2 weeks, each triad in turn was taken to a private room for a few minutes and asked about the collaboration process and their preferences for computer versus practical work. The teacher was interviewed at some length 4 weeks after the experiment; written questions were sent to her in advance and then posed verbally. A variety of issues were covered, including classroom management and organisation, worksheet materials, computers in the classroom, success of groupings, professional development and suggested improvements.

ANALYSIS

A coding scheme was constructed for the explanations elicited by the written diagnostic tests, through trialling versions of the items with about 90 children of the same age in other schools. Their responses were analysed and placed in categories - between 4 and 12 for each question - which were then used to help classify those which emerged from our sample and parallel classes. (Multiple codes were allowed, and there were additional global categories for ‘other’ explanations; those based on a child’s own experience; ‘mismatches with choice’; ‘unclassifiable’ i.e. nonsense/restatement etc; ‘no response or guesses’.) The process of clarifying and extending the coding scheme was iterative; it was revised whenever problems of ambiguity or new cases arose. The categories finally assigned to each question included a response consistent with the Newtonian view and a set of typical alternative conceptions revealed by the children's responses.

Three independent judges (each of whom had attained at least A-level standard in physics) used our coding scheme to code a sample of 13 scripts - i.e. a total of 286 responses each - randomly drawn from the experimental class data. The coding scheme proved to be reliable; using strict criteria whereby only exact matches were counted wherever multiple codes arose, there was 75% agreement between the categorisations made by the judges and those of the researcher who did the original coding. (This percentage was calculated by adding up the number of judges who agreed on a category for each question - per subject - and dividing by the maximum total score possible: 4 x 13 x 22. Note that due to the large number of categories relative to the number of judges, it was not possible to determine statistical reliability.)

Next, the second-level coding involved searching the data from each class at each time of testing for particular combinations of forced choices and explanations relating to each of the identified key reconstructions. These were used to identify children (a) giving 'correct' composite responses, (b) showing partial correctness or 'merit', and (c) exhibiting specific common prior conceptions. Strict criteria were used to rule out guesswork by omitting all low confidence responses (choices and explanations with confidence ratings < 2 on the 0-3 scale).

'Correct' responses reflected the target conceptions, namely those corresponding with the Newtonian perspective. There were responses, however, which indicated partially correct answers. These were cases where correct predictions were made, but where the reasoning was ambiguous or loosely expressed. An example of such a response is one in which a pupil gives 'friction' as an explanation for the deceleration of a sliding box, but without explaining how the friction acts to produce the deceleration. A response of this kind is closer to a Newtonian response than one in which the pupil attributes the cause of slowing down inappropriately, for example by referring to the force in the box running out. Such partially correct responses were given 'merit marks'. Merit marks were thus assigned to responses which included a correct forced choice prediction, together with a partially correct reason.

In addition to assessing the extent to which children's responses corresponded to the goal conceptions, an assessment was also made of the prevalence of identified prior conceptions. The specific prior conceptions which could be identified from responses to the test items are given in Table 3 with the numbers of applicable questions for each. The friction conceptions listed vary widely in terms of sophistication, including for example a complete lack of recognition that friction is a force opposing motion, as well as the understanding that its magnitude depends on weight. Since some ideas consistent with the Newtonian view were included, the friction conceptions could not be treated as a set in the same way as the force conceptions, and their prevalence on each test occasion was measured individually.

A series of statistical tests was carried out to examine persistence of responses over time. Evidence of the key reconstructions having taken place was sought by looking for increased correctness and sophistication of responses, increases in pupils' mean confidence ratings (over all questions) for each test, and decreased numbers of prior conceptions. Partial repeated measures analyses of variance (ANOVAs) were used to compare numbers of correct responses, correct responses plus merits (these categories are non-exclusive), mean confidence ratings, and total numbers of force prior conceptions, by subject and within each class over time (the between-subjects factor was sex).

Table 3 List of prior conceptions categories

'Force' prior conceptions (no. applicable questions)	
1	a moving object has force 'in' it (4)
2	force 'in' object runs out when object stops (3)
3	force must be in direction of motion; motion implies force (3)
4	forward force must be greater than retarding force to maintain constant motion (4)
5	objects 'drift around' in space (1)
6	no difference between 'getting going' and 'keeping going' (1)
7	heavy things fall faster than lighter things (1)
8	a moving object stops 'naturally' (1)
'Friction' conceptions (no. applicable questions)	
9	friction not included in explanation as a force opposing motion (3)
10	friction is included (5)
11	friction is 'glue' (1)
12	friction is directional (2)
13	an object slows down because of weight (3)
14	friction is related to gravity (1)

A series of between-class comparisons on all measures was then carried out using analyses of covariance or ANCOVAs (in order to adjust the post-test scores so that the dependent measures were the residuals after using the pre-test scores as a regressor). Least squares means analyses were performed after each analysis in order to isolate the specific source of all significant variations.

Change within individual prior conceptions was measured using a series of Wilcoxon matched-pairs signed-ranks tests. (Note that although the prior conceptions categories were not mutually exclusive, this was unproblematic since change was measured separately within each category.)

All analyses were carried out using the following criteria: ambiguous responses were given the benefit of the doubt, and multiple codes were treated as instances of each of their separate components. Since a child's conceptual framework may well include a combination of correct, partially correct and completely non-Newtonian beliefs, including only those occurring in isolation was felt to be unjustified.

Finally, it was deemed inappropriate to assess the internal validity of the coding scheme by comparing answers across related question contexts within a test because children are known to formulate highly context-specific theories in this domain (e.g. Champagne, Gunstone and Klopfer, 1985).

RESULTS AND DISCUSSION

A. Overall measures of conceptual change

Results of the ANOVAs carried out to measure increases in sophistication of responses over time within the experimental class are summarised in Table 4, and presented below along with results of the Wilcoxon tests which investigated change in terms of individual prior conceptions.

Table 4
Analyses of variance over time in four measures of conceptual change

Measure	Means (SDs) pre	post	delayed	*F* ratio	*p* values
No. correct	1.8 (1.5)	3.3 (2.1)	3.1 (2.4)	11.47	0.001
No. correct + merits	6.2 (3.7)	9.1 (4.7)	9.9 (4.4)	13.60	0.001
Pupil confidence rating	1.5 (0.7)	1.9 (0.9)	2.0 (0.9)	10.49	0.001
Total force conceptions	3.7 (3.0)	4.0 (2.5)	5.0 (3.0)	5.18	0.009

Note. Maximum totals are 24 correct responses, 21 merits and 18 force prior conceptions.

Table 5 Post-ANOVA effects analysis

Measure	pre/post *t*	pre/post *p*	pre/delayed *t*	pre/delayed *p*
No. correct	4.33	0.001	3.93	0.001
No. correct + merits	3.94	0.001	4.93	0.001
Pupil confidence rating	3.13	0.003	4.46	0.001
Total force conceptions	0.63	ns	3.05	0.004

1. Significant increases over time were found in (a) correct responses, (b) correct responses plus merits, and (c) overall pupil confidence ratings. The least squares means analysis revealed that the main effects emerging in each case reflected significant increases between both pre- and post-tests and pre- and delayed post-tests (see Table 5).

2. There was a dramatic decline between the pre- and delayed post-tests in explanations linked with two kinds of prior conceptions: 'motion implies a force in the same direction', and those whose explanation for slowing down did not include a reference to friction as a force opposing motion. (*T* values and significance levels associated with these results are listed below in Table 6.) Those individuals (n = 13) who gave fewer explanations in the latter category on the post-test were discovered to have replaced their beliefs specifically with two more sophisticated kinds of explanation: those including friction (n = 12) and those relating it to gravity (n = 5).

3. The above findings reflect the emergence of an interesting general phenomenon: there was in fact considerable evidence of children expressing certain other kinds of prior conceptions on more of the test items after the intervention than before it. The ANOVA results in Table 4 indicate increases over time in the total numbers of force prior conceptions. Table 5 shows that significant change became evident only between the post-test and the delayed post-test on this measure.

The Wilcoxon tests (see Table 6) showed that two kinds of prior conceptions in particular became more prevalent over time: 'forward force must be greater than a retarding force in order to maintain motion', and 'an object has force "in" it'. There was evidence, however, as has already been mentioned in paragraph 2, that more sophisticated conceptions relating to friction increased from pre- to post-test. More pupils used the conception of friction as a force opposing motion and the notion that magnitude of friction depends on weight. In addition, there was evidence for a greater understanding of resistive forces being directional.

B. Between-class comparisons

The exploratory ANOVAs carried out on data within the three parallel classes indicated that a substantial amount of conceptual change took place in pupils in only one other class (Class 3). This sample showed significant increases over time ($p < 0.01$) in numbers of correct responses and merits, pupil confidence, and also the total force prior conceptions. Since they were not given a delayed post-test, it is not known whether these changes persisted over time. Class 2 pupils demonstrated pre/post increases in correct responses and correct responses plus merits only, but even these had disappeared by the time of the delayed post-test. Similarly, Class 4 pupils showed no significant changes over time on any measure.

Our experimental group differed significantly from the others in one respect, being the only group to demonstrate a decline over time in any of its prior conceptions. The phenomenon of increasing prior conceptions was also less pronounced in the parallel classes, and the total extent of significant within-class change is shown in Table 6.

The results of the ANCOVAs carried out to investigate between-class variation on all measures are presented in Table 7. They provide a global picture of the differences arising in the (adjusted) post-test results. The only significant differences were that the experimental class produced more correct responses than Class 2, and more force prior conceptions than Class 3. In sum, the parallel classes did not show any increases over our experimental class on any measure, although on some measures, there were no significant differences between our class and a subset of the others.

While this report focuses on the diagnostic test results, the process of examining changes in prior conceptions over time also included analyses of (a) audiotape transcripts of the 18 diagnostic interviews, and (b) videotape and written records of pupil-computer interaction within the target group. The latter analysis entailed charting the learning trajectories of three individuals (as mentioned above, a report of this in-depth investigation of conceptual change is currently being prepared).

Table 6 **Significant within-class changes in prevalence of prior conceptions**

	Prior conception	Class	Time	↑ ¬	Wilcoxon result
1	a moving object has force 'in' it	E 2	pre/del pre/del	↑ ↑	$T = 13$, $p < 0.01$ $T = 5$, $p < 0.05$
2	force 'in' object runs out	3	pre/post	↑	$T = 5$, $p < 0.05$
3	motion implies force	E	pre/del	¬	$T = 21$, $p < 0.05$
4	forward force > retarding force (to maintain constant motion)	E	pre/del	↑	$T = 31$, $p < 0.02$
5	objects 'drift around' in space			no change	
6	no difference between getting going and keeping going			no change	
7	heavy things fall faster than lighter things			no change	
8	a moving object stops 'naturally'			no change	
9	friction not included	E 3	pre/post pre/del pre/post	¬ ¬ ↑	$T = 22$, $p < 0.02$ $T = 35.5$, $p < 0.05$ $T = 2.5$, $p < 0.02$
10	friction is included	E	pre/post pre/del	↑ ↑	$T = 7$, $p < 0.01$ $T = 5$, $p < 0.01$
11	friction is 'glue'				no change

12	friction is directional	E 2	pre/post pre/post	↑ ↑	T=11, p<0.05 $T = 4, p < 0.05$
13	friction depends on weight	E	pre/post	↑	$T = 8, p < 0.01$
14	friction depends on gravity			no change	

Note. E = Experimental class.
Note. ↑ indicates increased prevalence over time and ¬ indicates a decline in prevalence.

Table 7
Analyses of covariance by class in four measures of conceptual change

	Post-test Least Squares Means				F-ratio	p-value
Measure	class 1	class 2	class 3	class 4		
No. correct	3.0	2.0	2.2	2.7	2.26	ns
	(1.6	(1.6)	(1.6)	(1.6)		
No. correct + merits	8.5	7.0	7.1	8.9	1.51	ns
	(3.6)	(3.6)	(3.5)	(3.6)		
Pupil confidence rating	1.9	1.6	1.7	1.8	0.91	ns
	(0.6)	(0.6)	(0.6)	(0.6)		
Total force conceptions	3.3	3.5	2.9	4.3	1.96	ns
	(1.9)	(1.9)	(1.9)	(1.9)		

Note. Maximum totals are 24 correct responses, 21 merits and 18 force prior conceptions.

The interview results corroborated the test results, showing that the whole class data was representative. The transcripts of the interviews carried out before and after teaching were analysed with respect to each of three overall measures of conceptual change. Each individual pupil could be characterised as having prior conceptions of the type indicated by the combined data. There was no evidence in the transcripts of the post-teaching interviews that any new non-Newtonian concepts had been acquired. In each case the number of correct responses had increased and the pupils' confidence in the correctness of these responses was evidenced by their use of qualifiers (e.g. 'I'm sure') and by their vocabulary (e.g. 'friction force'). The change in vocabulary that accompanied discussion of balanced forces or friction as a force was very clear as was the sophistication of the answers (e.g. shifting from 'a thrown ball loses power' to 'gravity is pulling it down all the time'). In one case, the improvement in understanding evidenced by the transcripts of interviews before and after teaching was very small and the pupil remained at a very low level of attainment. In all the other cases the change was quite marked, particularly when pupils had acquired the concept of motion continuing in objects with balanced forces. In two cases, pupils who started from a view of only one force acting at a time and no concept of friction as an opposing force ended with an explicit account of both friction and balanced opposed forces.

The interviewers had carefully related their questions to the written tests previously completed by the pupils. The interview transcripts lead us to believe that the pupils completed the written tests accurately and carefully. They also suggest that the conclusions drawn in this paper from the quantitative data are very cautious and conservative. In the case of the initially lower scoring pupils, the interviews reveal a shift to an appropriate vocabulary ('friction', 'opposing force', 'gravity', 'balanced forces'). In the case of the initially higher scoring pupils, the interviews before teaching indicate in some cases that correct answers to the written tests are accompanied by doubt and inability to justify answers. After teaching, the same pupils were able to justify the same correct answers with appropriate reasons. Another encouraging aspect of the interviews is that the pupils very rarely appealed to particular experiments or simulations that they had used in the teaching to justify their correct answers. In summary, then, the analysis of the interview data provides another source of evidence for cognitive change measured in the quantitative data; it suggests that the written tests provide an accurate reflection of the pupils' understanding; and it indicates that the learning gains were much more substantial than those that can be documented via the grouped numerical measures.

C. Sex differences

Sex was included as a factor in all statistical analyses but no significant effects or interactions emerged. This is surprising given the results from other studies of children working with (Scanlon et al, 1993) and without computers (Johnson and Murphy, 1986) on science activities. However, observers did comment on the greater degree of cooperation apparent in the behaviour of the female versus the male groups; the latter acted more competitively. Note that this research was not designed to investigate sex differences. We made particular efforts to design scenarios which appealed to both boys and girls, and this proved successful; our findings on conceptual change show no particular advantage for either sex. (This issue is discussed further by Scanlon et al, 1993).

D. The activities and their social context: observations and interview conclusions

One of the most important indicators of an experiment's success is the subsequent opinions of those who took part. Responses from the teacher and pupil interviews reinforced each other and were generally favourable, but gave clear pointers for future improvements to the materials and lesson organisation. The main conclusions we drew were as follows:

First of all, the triad groupings were moderately successful; there was a lack of cooperation in a few cases where one person was either socially excluded by the other two or tended to work at a much faster pace. Since children of this age are often competitive and reluctant to work with members of the opposite sex, the ideal groupings would probably be single-sex pairs or ability-matched threesomes. Responses were collected from individuals rather than groups because this was deemed to be more representative and to overcome distraction of the two non-scribes, but in practice one child often took the scribe role and others copied. This was problematic because a joint view was not necesarily reflected in the group's output, and it was difficult to get children in such groups to engage in discussion.

With regard to between-group interaction, knowledge about the tasks or the DM^3 interface was rarely found to be shared between pupils in different triads. The vast majority of interaction was social, and even this was not extensive, perhaps because the culture in the classroom under observation normally discourages socialising, or owing to the presence of researchers in the room.

The lack of collaboration between groups also reflected the graspability of the software and materials; no particularly problematic features were isolated and pupil requests for explanation were very rare. The extensive pilot testing proved to be very fruitful in rendering the direct manipulation interface to DM^3 intuitive and easy to learn, and therefore highly successful in this context. The cooperative nature of the activities was clearly an aid here, providing some evidence confirming previous findings which show that joint problem-solving with computers - particularly by pairs - facilitates learning (Howe et al, 1991; Trowbridge, 1987). The children were even quicker to grasp the software's functionality when working as a team than individuals had been during the earlier trials. Difficulties previously detected with interpreting speed-time graphs appeared to be spontaneously ironed out, probably because the graphing facility was a constant feature throughout all scenarios and most of the worksheet tasks depended heavily on its use. Dependence on the graphing facility proved particularly effective in helping children recognise that there are distinct phases of motion, requiring different force explanations.

The interviews yielded some information about the children's and teacher's opinions of the materials themselves. There was a strong belief that the computer medium offered something of value and that the half-and-half balance between computer and practical activities was successful. The teacher felt that the computer's particular strength lay in allowing children to alter parameters easily and without the problems which other confounding factors normally contribute. Pupils were able to gather data sets quickly, without continually having to set up cumbersome experimental apparatus. The computer's instant measurement and feedback features helped not only to maximise experience with the simulated phenomena, but also contributed towards the greater reliability of experiments within the simulations than of practical demonstrations; as is often found, the latter occasionally failed to work convincingly, because various factors were difficult to control. In the teacher's own words,

> The computer provided an opportunity for the children to investigate, where in fact there was an outcome. They could actually achieve the desired outcome in most ordinary experiments, but I should say in 8 out of 10, they don't actually achieve it, simply because of problems with apparatus etc...They could do an experiment and do everything as they should have done it, but at the end of the day, they still haven't actually discovered any patterns. Not because they've done anything wrong but because the apparatus is limited and because the situation that you're in is limited... I think the computer reinforced what we'd talked about and where experiments had been doubtful, it possibly helped them to see how things really did work.

In sum, the simulations proved particularly beneficial for those situations which are tricky to demonstrate in a normal school environment. It was outside the scope of the project to examine the implications for learning transfer of a distinction between real world objects and their representation within a computer world; there is a potential risk that unfamiliar or 'cleaned-up' events on a computer will destroy belief in computer simulations generally (see Hennessy and O'Shea, 1993). Nevertheless, the pupils appeared to discriminate easily in this context between realistic and unrealistic simulated phenomena. The teacher shared this perception and was very enthusiastic about the inclusion of imaginary situations (such as the worlds where friction could be manipulated):

> I think it gave leeway for them to appreciate that there is a real world in which there were certain restrictions, rules, laws that were obeyed. And that in an imaginary situation, a magic world, those laws weren't obeyed. I think it actually reinforced that the real world has got laws; also, it was fun for them which I think is a very important part of the whole thing.

However, as is often reported, a confirmatory bias was occasionally evident, whereby children's informal conceptions affected their predictions, perceptions and interpretations of both physical phenomena and computer representations of those phenomena. This was confounded by the lack of control apparent in their experimentation, and their failure to appreciate margins of error in measurement, again in both the computer and practical contexts.

Our computer tasks were atypical in being more prescriptive than normal science activities, requiring less responsiveness and adaptation from the teacher. The worksheets may in fact have been too structured, leading to the teacher believing that the computer-based work required less teacher input than the practical work. A clear message from both teacher and pupils was that the deliberate predictability of the task presentation was unsuccessful; the format rapidly became familiar, with a corresponding loss of motivation. In sum, more variety of tasks, some less structured activities and some more entertaining or creative ones would have been preferable. As a first step, more scenarios with the same underlying physics but different task presentation could be included. On a more positive note, a significant Hawthorne effect is unlikely to have occurred; the interviews showed that the glamour and novelty of using sophisticated technology and a new kind of activity in science lessons soon dissipated. Moreover, the teacher's general response to the worksheets was very positive. She assured us that she would use them in her future teaching, especially the homework sheets:

> All the worksheets had the very desirable feature of being designed for children to grasp concepts rather than facts. It's easy otherwise to find yourself giving them facts, which is less painful for the children.

As is probably the case with any form of instruction (and thus confirming our expectations), the children's agenda appeared different to those of the researchers and teacher. Their aims and expectations differed from ours in general; they expressed no desire to grasp Newtonian concepts or to alter their existing conceptual frameworks. This disparity was encapsulated in a plaintive remark made by one subject, Craig, to the teacher: "Oh miss, you're just saying that, just to make us think"! Specifically, the children were used to doing more practical work in science and many claimed to prefer it to the computer activities because it is 'messy' and offers more pupil control. From the point of view of the teacher and observers, the practical sessions evoked less productive discussion and more social interaction than did the computer tasks, and the children's apparent mental separation of the two kinds of activities meant that there was very little explicit transfer between them.

Finally, our attempt to achieve 'ecological validity' was ambitious but on the whole successful: the materials proved usable in an ordinary classroom context by a teacher with no special background training; the experimental sessions fitted in with the school's normal timetable for this subject; all logistical issues were satisfactorily resolved during the 2-week pre-trialling period. Obviously, the presence of several researchers, computers, tape recorders and a video camera in the classroom was extraordinary, but the time period (7-9 weeks) proved long enough for the children to become accustomed to this novel situation. (The teacher perceived that the children ceased to be markedly affected by it after the first few weeks.) The length of the intervention was nevertheless problematic; although the children were considered to have achieved as much as they and their teacher expected, a longer time would probably be needed to accomodate Newtonian concepts more fully. The teacher additionally suggested that computers ought to be presented as a more flexible resource - ideally being available in the classroom for use whenever needed - although practical constraints make this difficult with a large class.

Let us conclude by considering the teacher's overall impressions of the intervention's outcomes in terms of her own development as well as her pupils' progress:

> The GCSE topic we do has a very cursory approach to forces so the material made me think quite a lot. I asked other Physics teachers about some of the issues and it made them think! This experience has uncovered weaknesses in my own conceptual world, hopefully fewer weaknesses than the children! This happens all the time anyway, it's good, it makes it more interesting and more challenging...
>
> Whereas older children accept what you tell them, in the way this was set out it was hard for the children to do that. We've all learned from it. I think it's very worthwhile, much more so than many of the innovative things that we do because it involves the children... I've picked up some negative vibes indicating that spending such a lot of money must be a waste of time and many innovations are, but here the first priority is the children's progress, so money spent on this is not a waste of time.

CONCLUSIONS

It has been demonstrated that a curriculum oriented around multiple computers situated **inside** an ordinary science laboratory or classroom is both feasible and effective. The results of the classroom evaluation study indicated that the integrated curriculum was successful in facilitating understanding and assimilation of some Newtonian concepts in children aged 12-13. Despite the typical reluctance of schoolchildren to relinquish their informal theories in this domain, an encouraging amount of conceptual change - significant on all of the measures examined - was elicited over a relatively short time. In addition to more ‘correct’ responses from the Newtonian perspective, the curriculum promoted more sophisticated explanations of motion. The charting of conceptual change at this level of detail was possible because our analyses were unconventional to some extent: they focused on qualitative shifts in response patterns - including forced choice and explanation combinations - rather than merely on increases in ‘right’ answers. Furthermore, the intervention served to increase teacher awareness of children’s informal ideas as well as pupil awareness of the scientific viewpoint.

Interaction with *DM*^{3} additionally appeared to help make children aware of inconsistencies in their own reasoning, some of which are more robust than others; an interesting outcome was the increased prominence of certain kinds of informal conceptions over time. It appears that concentrated study of the topic of mechanics can reinforce some of the ideas which pupils already hold. One explanation is that activities involving discussion with peers and in-depth experimentation may in fact help pupils’ informal theories to become more explicit, assisting them in better articulating those theories (as well as rendering them less likely to misunderstand the questions posed). Consistent with this explanation is the possibility that situations which challenge pupils’ robust beliefs give rise to their creative simplification of the problems encountered, whereby complicating factors are simply ignored (Karmiloff-Smith and Inhelder, 1974/5).

The increase over time in pupil confidence supports the above account, as does the fact that children of this age cannot formulate coherent causal explanations for certain phenomena, neither pertaining to their informal beliefs nor in correct physics terms. For instance, a question comparing relative amounts of air resistance when cycling at a slow versus a fast steady speed elicited a very high proportion of correct choices, but these were accompanied by a huge variety of inadequate, vague explanations. One child simply stated "Because it’s life"! (This finding reinforces the necessity of eliciting explanations of motion in order to discriminate between informal conceptions.) However, in other cases, increases in prior conceptions reflected a qualitative shift towards more sophisticated ideas. For example, explanations excluding the notion of friction were displaced by those including it and in the experimental group, also by those relating friction to gravity.

This investigation has highlighted the apparent co-existence in the children's minds of conflicting theories of motion. These may be context-specific, relating to particular physical settings or, for instance, denoting a separation between horizontal and vertical motion. Subsequent conceptual development will be necessary to overcome this implicit conflict, so that more precise relationships between physical variables can be developed and links be made between the isolated pieces of knowledge that appear to be present. While some of the most primitive prior conceptions elicited in our sample will need to be replaced, others are believed to be representative of an important stage in conceptual development in this domain. These ones can probably be fruitfully built upon; for example, the notion that 'getting going is harder than keeping going'. Further analysis of the target pupils' work was undertaken to identify trajectories in the routes pupils take in restructuring their reasoning and the results will be reported elsewhere.

The results of our intervention are in keeping with Osborne's (1985) assertion that children under 14 years are a suitable age group for this kind of study, being more motivated and flexible in their ideas than older children. The process of conceptual change is a gradual and cumulative one and the intervention was relatively short (though actually longer than many schools spend on this topic). A much longer period of structured pupil activity would obviously be necessary for more radical conceptual change to occur and as Bloom (1993) has pointed out, true changes in allegiance may require an enormous amount of personal reflection and re-evaluation of beliefs and expectations. However, intervening at the very beginning of formal teaching in the domain does seem to provide us with an optimal chance of success. To conclude, it has been demonstrated that a curriculum integrating simulated computer experiments with conventional practical activities is an effective tool for helping learners change their understandings of mechanics.

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